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An Evanescent Microwave Probe for Super-Resolution Nondestructive Imaging of Metals, Semiconductors, Dielectrics, Composites and Biological Specimens

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Abstract

Using evanescent microwaves with decay lengths determined by a combination of microwave wavelength (λ) and waveguide termination geometry, we have imaged and mapped material non-uniformities and defects with a resolving capability of $\lambda/3800 \approx 79$ µm at 1 GHz. In our method a microstrip quarter wavelength resonator was used to generate evanescent microwaves. We imaged materials with a wide range of conductivities. Carbon composites, dielectrics (Duroid, polymers), semiconductors (3C-SiC, polysilicon, natural diamond), metals (tungsten alloys, copper, zinc, steel), high-temperature superconductors, and botanical samples were scanned for defects, residual stresses, integrity of brazed junctions, subsurface features, areas of different film thickness and moisture content. The evanescent microwave probe is a versatile tool and it can be used to perform very fast, large scale mapping of a wide range of materials. This method of characterization compares favorably with ultrasound testing, which has a resolution of about 0.1 mm and suffers from high absorption in composite materials and poor transmission across boundaries. Eddy current methods which can have a resolution on the order of 50 µm are restricted to evaluating conducting materials. Evanescent microwave imaging, with careful choice of operating frequency and probe geometry, can have a resolution of up to 1 µm. In this method we can scan hot and moving objects, sample preparation is not required, testing is non-destructive, non-invasive and non-contact, and can be done in air, in liquid or in vacuum.

Introduction. Evanescent fields have been used to resolve features smaller than the classical Abbe limit [1]. Ash and Nicholls were probably the first to come up with the idea of near-field scanning for microscopy. They were able to resolve features on the order of $\lambda/60$ in one dimension and $\lambda/20$ for 2-dimensional objects. Atomic resolutions are achieved by using evanescent electron wavefunctions used in scanning tunneling microscopes. Near-field optical scanning microscopes also use evanescent fields, which can provide resolutions on the order of 10-100 Å using light of 6000 Å wavelength. Recently, a spatial resolution of the order of 5 µm has been achieved using evanescent microwaves. These fields have been produced at the end of coaxial resonators, by drilling a small hole in a waveguide or at the end of a transmission line.

Probe Design and Principle of Operation. Our probe, as shown in figure 1, consists of a quarter wavelength microstrip line resonator fabricated on Duroid substrates of different permittivities. The resonator is coupled to a short feedline by a three-fingered interdigitated capacitor. This capacitor can vary the coupling from under coupled to critical to over coupled. The tip of the resonator is tapered to localize the evanescent fields extending out of it. The spatial extension of these fields determines the resolution of the probe.

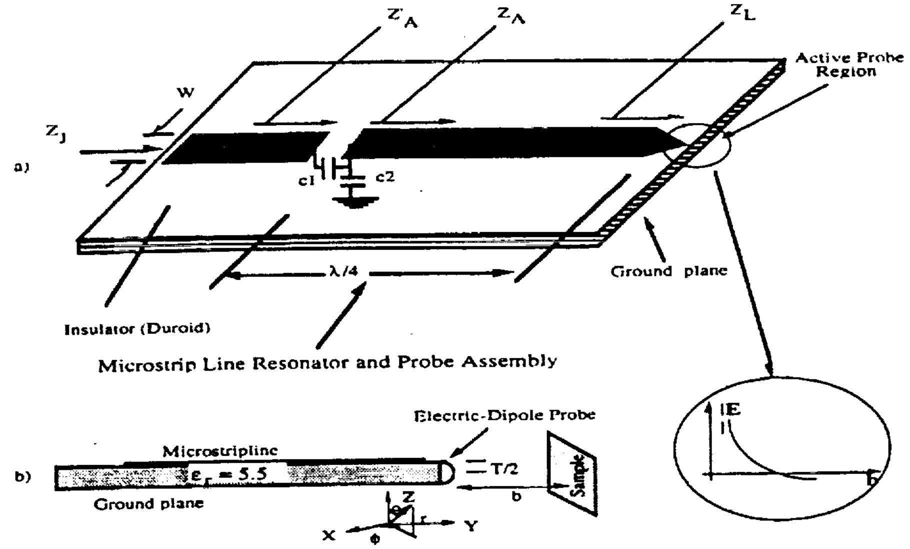

Figure 1 a) Microstrip line resonator and probe assembly. Evanescent waves extend out of the tapered tip of the resonator. b) The electric dipole probe is modeled as a microstrip line with a short length of current carrying wire. The current is assumed constant over the entire length of the wire in calculating the electric fields around the probe.

Figure 2 shows the shift in the resonant frequency as a copper plate is brought in from infinity to close to the probe tip. In metal samples defects and stresses can locally change the conductivity, and hence can be detected by the microwave probe. In the case of semiconductors the probe output can be affected by variations in carrier density, interface trap density, defects, presence of mobile or fixed charges, grain boundaries and variations in film thickness. In an earlier work the change in the amplitude of reflection coefficient as a function of the microwave frequency and carrier concentration in Si has been reported. For composites, their mechanical, chemical and physical properties influence a change in the permittivity of the material and can be detected as a change in the reflection coefficient.

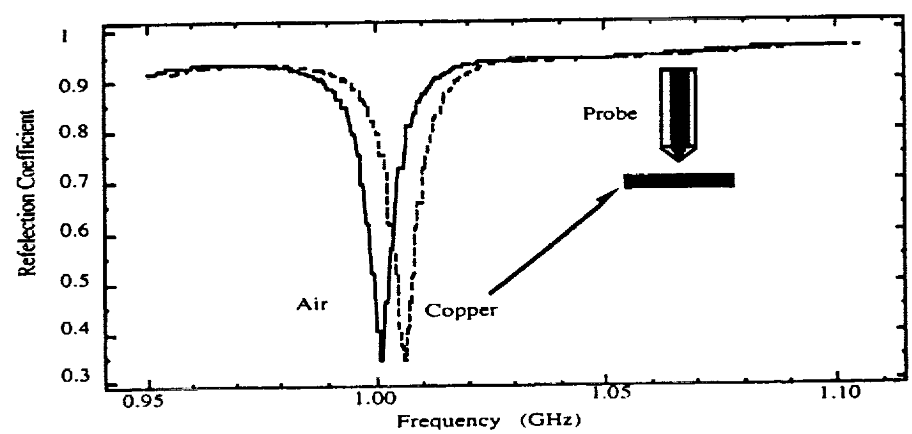

Figure 2 The presence of a copper plate close to the probe shifts the resonant frequency by 6 MHz. This shift in resonant frequency can be used to implement the probe as a proximity sensor.

Our experimental set-up consists of a quarter wavelength microstripline resonator based electric dipole probe as shown in figure 1. The resonator is coupled to a feedline which is connected to port 1 of a three port circulator. Port 3 of the circulator is connected to a 10 KHz to 1.05 GHz signal generator, and port 2 to a crystal microwave detector. The detector output is a DC voltage proportional to the magnitude of the reflected wave. This is fed to an amplifier and thence to a multimeter. The detector, circulator and probe circuit are mounted in a metal box with the tip of the probe protruding through a hole. The box is supported vertically over an x-y stage. The x-y stage and the frequency generator are controlled by a personal computer. The computer also acquires data from the multimeter. For improved SNR the sample platform of the x-y stage is vibrated at close to 90 Hz and the detector output is fed into a lock-in amplifier for synchronous detection.

Dielectrics. Figure 3 shows a microwave resistivity image over a 6.5 cm by 2.4 cm region of a carbon composite. These composites are layered structures glued together. We can detect the subsurface step 2 mm below the surface of the composite from the graph. The scan over the composite shows large variations in the microwave properties. These could be due to the glue diffusing into the composite material. A metal piece placed in the region of the subsurface step changes the probe response, proving beyond doubt that it is possible to detect at least 2 mm deep features in the composite. In our experiments with composites we also found that repeatable scans over dry composites changed dramatically when the composites were wetted. It should be possible to calibrate the change in probe response to the moisture content of the sample. We have imaged delaminated composites as well. Scans over intact and delaminated sections of composites depict a marked change in the probe response.

Figure 3 This is a 1 GHz evanescent microwave graph of a 6.5 cm by 2.5 cm region of a carbon composite, a schematic of which is shown in the figure.

Semiconductors. Figure 4 is a 2-dimensional pseudo colored scan of a 4" 3C-SiC/Si wafer. Growth and deposition of large area SiC films on Si are a problem because of the variations in film thickness due to gas flow, the formation of voids at the interface, and other defects such as stacking faults, threading dislocations, and anti-phase boundaries. Exploring the possibility of using our probe as a non-contact, non-invasive, non-destructive characterization tool for SiC films in particular and semiconductors in general we scanned a 1.5 μm layer of SiC on Si. The results were exciting as the pseudo colored plot of the scan seems to show variations on the wafer which match those that can be visually observed. These variations are primarily thickness variations due to gas flow which give the wafer a spectrum of colors as one goes from one end to the other.

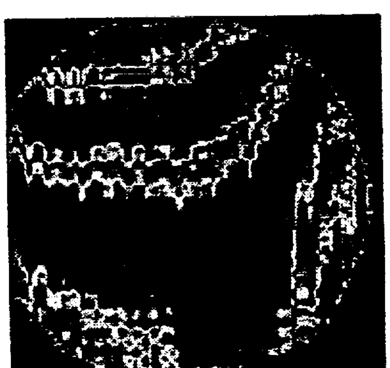

Figure 4 Evanescent microwave image of a 4" 3C-SiC/Si wafer. Variations in film thickness due to gas flow, which can be seen by the naked eye as rings of different colors, are here detected by the evanescent microwave probe. The scan consists of 130 X 130 points over the wafer.

Metals. Figure 5 shows an optical and a microwave image of a 2 mm diameter hole in a copper plate. A linescan over the same hole (figure 6c) can detect burrs on the edge of the hole. Earlier it has been reported that for small features (less than 0.5 mm) the probe gives double peaks due to asymmetry in the fields. But the peaks seen in this linescan at the edges of the hole are not found in scans over other similar holes implying that they are due to the burrs on the edge of the hole. Scans over grooves of known depth in the same copper plate were taken to characterize the probe output with respect to the depth of the strips.

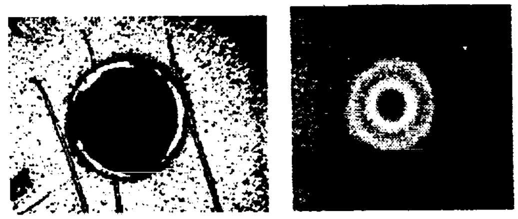

Figure 5 a) An optical micrograph of a 2mm diameter hole in a 6 mm thick copper plate.
b) An evanescent microwave image of the same hole.

Biological Specimens. Figure 6 shows a pseudocolor microwave image of a fresh leaf. A similar scan using a dry and damaged leaf was also performed. The moisture content as well as some basic features of the leaf can be detected using our probe. This technique, being non-contact, non-invasive, non-destructive, and capable of operating in any medium, is ideal for studying biological specimens in buffer solutions and in air. We are currently in the process of performing imaging of soft and hard biological tissues.

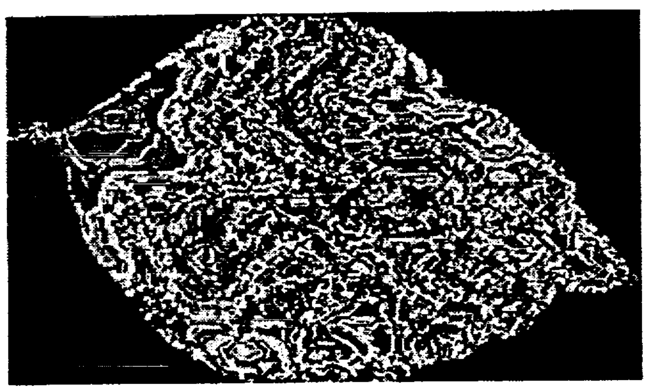

Figure 6 An evanescent microwave scan of a fresh leaf.

We have demonstrated the potential of the our evanescent microwave probe in detecting stresses, defects, non-uniformities, delaminations, moisture content, variations due to gas flow, and microwave conductivity in metals, composites, dielectrics and semiconductors. Various designs of the probe were studied. The probe was used to image Tungsten alloy samples, 3C-SiC/Si and Si wafers, Carbon composites, brazed junctions, BT sensors, and botanical specimens. The pseudo colored plots can identify regions of subsurface stress in metals and semiconductors, subsurface features, delaminations, and moist regions in composites, and variations in film thickness on a semiconductor wafer. Our work conclusively brings out the usefulness of our evanescent microwave probe for characterization of materials.

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References

[1] M. Tabib-Azar, N. S. Shoemaker, and S. Harris, "Non-destructive characterization of materials by evanescent microwaves." Meas. Sci. Technol. 4 (1993) pp. 583-590.
[2] M. Tabib-Azar, et al, to be published.